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SOLID-STATE ACTIVE SENSING FOR IN-SITU HEALTH MONITORING

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Abstract: Currently, there exists a need for sensors which can perform on-line health monitoring of structures. Such sensors will lead to utilization of a greater fraction of useful life, greater reliability, and reduced maintenance and inspection cost. An on-line health monitoring sensor system must meet three requirements: i) it must be small, non-intrusive, and must offer the possibility of being located in inaccessible remote areas of the structure and, as yet, it must be able to transmit information easily to a central processor; ii) it must be as sensitive as conventional non-destructive evaluation (NDE) techniques, i.e., it must be able to detect minor cracks; and iii) it must be able to monitor a certain minimum area of the structure as opposed to the point measurements offered by presently available NDE equipment. Our recent research efforts indicate that the piezoelectric (PZT) materials used as sensory actuators may meet these requirements. The method being investigated relies on tracking the high-frequency (typically > 50 kHz) point impedance of the structure through a surface-bonded PZT to qualitatively identify damage. At such high frequencies, the technique is comparable in sensitivity to sophisticated traditional NDE techniques, and is capable of qualitatively detecting incipient-type damage by looking at changes in structural impedance. As yet, it can be implemented in a remote sensing scenario. Several case studies involving built-up complex structures will be presented to demonstrate the potential benefits of the technique.

Key Words: Damage detection; health monitoring; impedance approach; nondestructive evaluation (NDE); smart structures

INTRODUCTION: A new qualitative non-destructive evaluation (NDE) sensor system to perform in-situ on-line monitoring of critical sections of structures and to provide a warning in the event of damage is the focus of this paper. How this new method differs from conventional NDE techniques like ultrasonics and X-rays, is in its ability to monitor a relatively larger area with minimal intrusion. While these conventional techniques can pin-point microscopic damage, they require ready access to the area as well as relatively large pieces of equipment. Such access, in some cases, is simply not available and in other cases can mean taking the structure out of service. Taking the structure out of service in itself can cause major disruption; in addition, the process is usually very labor intensive and costly.

Therefore, the need to develop a sensor system which can be permanently and non-intrusively installed in the critical sections of the structure to monitor their integrity. How does the new method overcome the limitations of the conventional NDE equipment and strain gage sensors? The new method employs high frequencies (typically > 50 kHz) at which there is a measurable change in structural point impedance even for minor damage such as small internal cracks, surface cracks, and loose connections. As yet, it can be implemented via small non-intrusive surface-bonded transducers for remote on-line monitoring. With regard to strain-gages and such local strain measuring techniques: first, the new method does not need a calibrated load on the structure since the actuator-sensor itself provides the excitation; and second, it can monitor a relatively large area. The extent of the area the sensor system can monitor is certainly much larger than a strain gage; but, the exact sensing range is not exactly known.

The proposed sensing system and methodology, in principle, utilizes the changes in the vibration/impedance signature (due to damage) to qualitatively identify damage. But, it is different from modal analysis-based methods. The fundamental difference lies in the frequency used to interrogate the structure, i.e., excite and sense the resulting vibration magnitude and phase. The frequencies used in this technique are much higher than those typically used in modal analysis-based methods. To sense incipient-type damage which does not result in any measurable change in the structure's global stiffness properties, it is necessary for the wave-length of excitation to be smaller than the characteristic length of the damage to be detected [1]. Finding damage when it is at an incipient level and before the global structural integrity is compromised, is most useful. This is because it can provide us with a warning before actual failure occurs.

The proposed technique described in this paper utilizes small PZT patches to provide high-frequency excitation, typically in the high kHz range, to the structure being monitored. At such high frequencies, the response is dominated by local modes and incipient damage like small cracks, loose connections, and delaminations, produces measurable changes in the vibration characteristics. The high frequencies also limit the actuation/sensing area. The effect of excitation frequency, geometry, material properties, structural joints, etc., on the size of the sensing/actuation area is still under investigation, but it is our observation that the sensing area, as a minimum, extends to the boundaries of the solid member to which the PZT is bonded. This limited sensing area helps to isolate the effect of damage on the signature from other far-field changes in mass-loading, stiffness and boundary conditions. The insensitivity to far-field boundary conditions comes at the cost of a limited sensing area. Therefore, this technique will be most useful in identifying and tracking damage in those areas of structures where high structural integrity must be assured at all times.

ELECTROMECHANICAL PRINCIPLES: Piezoelectricity describes the phenomenon of the generation of an electric charge in a material when subjected to a mechanical stress (direct effect), and conversely, a mechanical strain in response to an applied electric field (converse effect). Contrary to most applications where the piezoelectric material is either used as a pure actuator or as a pure sensor, this signature acquisition method utilizes the direct as well as the converse effect allowing for simultaneous actuation and sensing (e.g., collocated actuator/sensor) of the structural response. A PZT bonded or attached to a structure, and driven by a fixed alternating electric field, excites and induces vibrations in the structure. Meanwhile, the resultant vibrational response, which is characteristic of the particular structure, modulates the current flowing through the PZT. This modulation is representative of the degree of mechanical interaction between the PZT actuator-sensor and the structure at different frequencies. In electrical terms, the variation in the current modulates the electrical admittance, which is defined as the ratio of the resulting current to its energizing voltage. The admittance signature then provides the same information, and serves the same purpose as the conventionally known transfer function. The size of the PZT patch-sensor required to get a good vibration signature is typically small (less than a 0.5 sq. in., .01 in. thick). This allows for non-intrusive installation.

Mechanical impedance (the reciprocal of impedance) is defined as the ratio of the applied force and the resulting velocity. Analogous electrical impedance is the ratio of the applied voltage and the resulting current. Electromechanical transducer materials such as piezoelectrics provide a means for coupling the mechanical and electrical impedance. This allows for the extraction of vital mechanical impedance information from pure electrical impedance measurements. The electrical impedance measurements are greatly facilitated by use of a commercially available impedance analyzer. In the electrical impedance *vs.* frequency measurements, the structural resonance will show as sharp peaks above the base-line electrical capacitive impedance. Since these peaks correspond to specific structural resonances, they constitute a unique signature of the structure's dynamic behavior. Therefore, any change in the impedance is considered an indication of structural integrity variation.

PROOF OF CONCEPT APPLICATIONS: To date, the new health monitoring method has been applied to a wide variety of situations in the laboratory. A brief outline of the successful applications done at CIMSS is presented.

Aircraft Fuselage [2]: The tail section of the Piper Model 601P airplane was selected to test the NDE technique on complex structures. The goal was to monitor the integrity of the two main brackets which connect the rear fuselage to the vertical tail. PZT patches were mounted on the fuselage side of the vertical tail support brackets, each within one inch of the two securing bolts (Fig. 1).

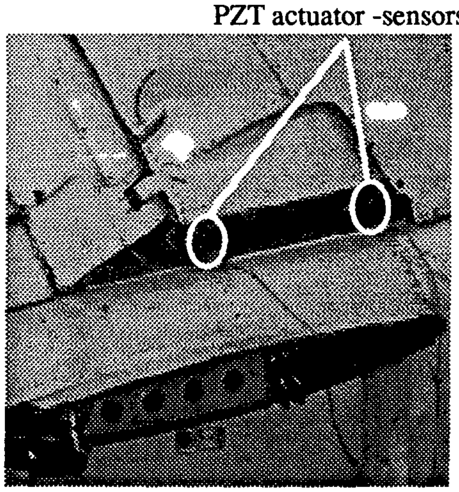

Figure 1. *The integrity of the two main brackets which connect the rear fuselage to the vertical tail of a Piper Model 601P airplane was monitored.*

The experimental results for the bolted aircraft joint are presented below. The two graphs in Fig. 2 show the real admittance measurements of the PZT actuator/sensor with local damage and global damage, respectively. The change in the electrical admittance measurements with a small defect (smallest possible

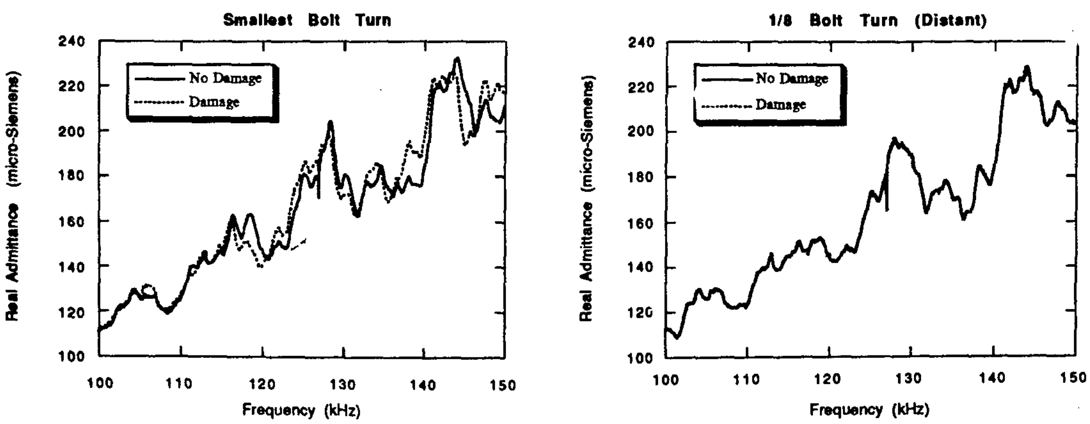

Figure 2. *Graph on the real electrical admittance of the PZT actuator-sensor. Note the large variations in the values of the local bolt, while the distant bolt values remain unchanged.*

turn of the connecting bolt) is significant while the measurements are unaffected by distant damage. The principal conclusions drawn from this work were that: i) the technique, because of the high-frequency, is very sensitive to minor change; ii) the actuation-sensing area is limited to a small area. The localization of the sensing area provides a practical means of utilizing vibration/impedance measurements to monitor critical sections of structures.

A scalar damage index used to simplify the interpretation of the impedance changes is shown in Fig. 3 for the aircraft bolted joint, with five different types of damage, both local and far-field. The damage index is defined as the sum of the differences of the real admittance change, squared at each frequency step. This damage index is then normalized to 100% with respect to the local smallest bolt turn to which all other damage is then relatively compared. A larger damage index than 100% means more structural damage than the reference smallest bolt turn. The principal advantage of this damage index is the facilitation of the result interpretation. Based on the damage index, damage can be reported to the operator automatically when a threshold value is reached, in a green/red light form.

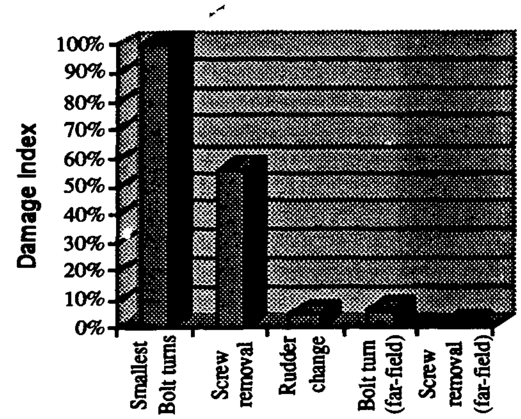

Figure 3. *Damage index of a bolted joint between the fuselage and the vertical tail of an aircraft subjected to various local and far-field alterations.*

Composite Repair Patch [3]: Critical to the success of composite repair of metallic aircraft structures is the integrity of the bond between the base aluminum panel and the reinforcing high-strength composite patch. Monitoring of the repair is equally important to ensure the integrity of the composite patch throughout the service life of the structure. The new NDE method was applied to test coupons repaired with a composite patch to monitor the growth of the crack under fatigue loading (Fig. 4). The detection of debonds in the composite repair patches was also investigated.

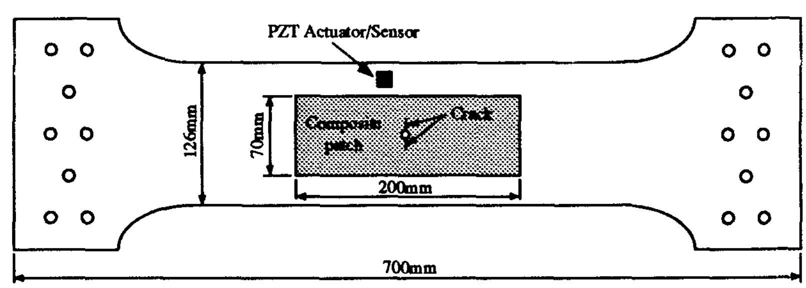

Figure 4. *An aluminum dog-bone specimen with a small crack was repaired with a bonded graphite/epoxy composite patch.*

The electrical measurements of the dog-bone specimen before and after the crack growth are presented in Fig. 5. A clear shift in the resonant frequencies can be observed, indicating a change in the structural properties of the specimen, i.e., crack growth. Similar tests performed on dog-bone specimens without composite repair patches showed similar variations in the admittances measurements. Also, very minor debonds between the composite patch and the metal base structure were qualitatively detected.

Deck Truss Bridge [4]: To this point, the research has involved relatively light structures. In this next proof-of-concept demonstrator, a massive one-quarter model of a steel deck truss bridge joint that experienced in-service failure is investigated. The size of the demonstrator is 72 inches tall, 41 inches wide, and over 12 inches deep (Fig. 6). The entire structure weighs more than 500 pounds and is considered representative of a typical high-strength civil engineering steel structure. Three piezoceramic incipient damage actuator/sensors were bonded at critical locations on the structure. As for the aircraft structure, local and global damage due to loose co...ections and structural damage was investigated.

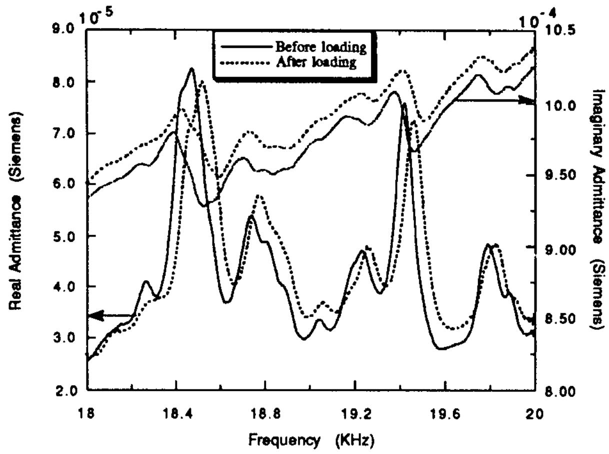

Figure 5. *Effect of crack growth on the admittance measurements of the dog-bone specimen with a graphite/epoxy repair patch .*

In Fig. 7, the admittance measurements for the healthy structure and the damaged structure (one loosened local bolt) are shown. It is to be noted that loosening one of the six bolts constituting the connection between the two structural members does not constitute a change in the global stiffness of the structure; in fact, it is quite comparable to incipient-type damage. In the experiments, the incipient damage manifested itself as a vertical shift of the admittance, which differs from the previous cases were a non-uniform horizontal admittance change was observed. This different behavior was attributed to the high stiffness of the structure. Nevertheless, the nondestructive evaluation technique demonstrated the capacity of detecting incipient damage once again. The results also indicated that the technique has the potential for quantifying damage: the effect of two loose bolts is almost double that of a single bolt. The localization phenomena of the NDE technique was once again observed.

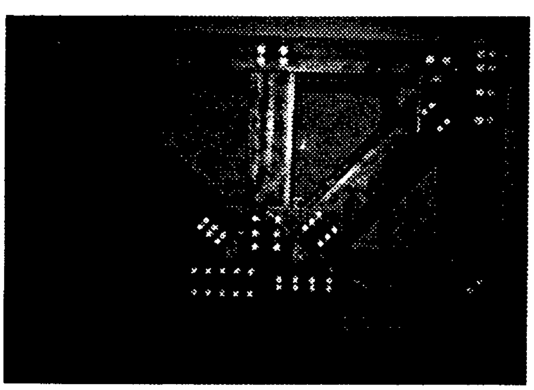

Figure 6. *A quarter-scale model of a bridge joint was used to study the NDE technique in massive structures.*

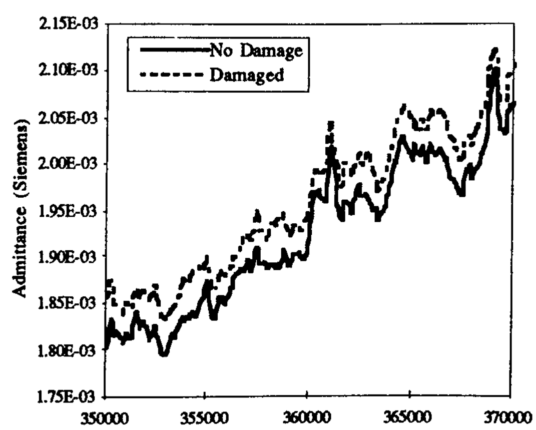

Figure 7. *The loosening of a local bolt has the effect of shifting the admittance measurements.*

Precision Parts [5]: The application of the impedance-based technique was then extended to high- precision parts. Gears were chosen as complex precision parts for the experimental procedure because of their high tolerances, high quality, and broad use. The goal was to show that incipient damage in the gear teeth, which are an extension of the base structure, can be monitored. The most common types of damage in gears, i.e., abrasive wear and bending fatigue cracks, were successfully detected. The impedance measurements before and after damage were converted into a scalar damage. Also, quality inspection was successfully demonstrated using the impedance-based technique.

In Figure 8, the damage metric of two frequency ranges for the adjacent (0°) and distant (90°) cracks is shown to be dependent on the frequency range. A greater structural activity in a frequency range, which reflects in an impedance reading consisting of many peaks and valleys, will cause the damage metric to increase because more variations in the impedance are present. A dynamically active frequency range should be picked for increased sensitivity of the impedance-based health monitoring techniq ie. Also, as mentioned earlier, the damage metric is larger for adjacent cracks to the PZT actuator/sensor due to the localized effect. The damage metric for the abrasive wear is also shown in Figure 8. The damage created by the wear of the gear teeth is less important than the damage created by the crack.

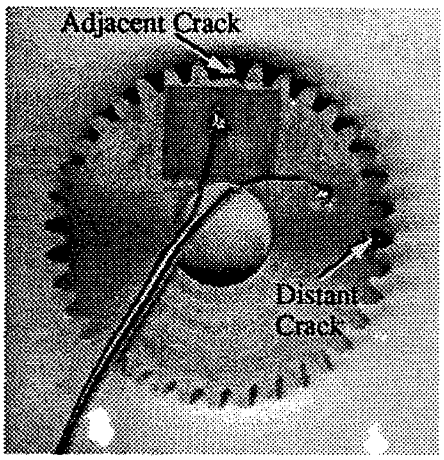

Figure 8. *Detection of bending fatigue cracks and abrasive wear in high-precision gears was investigated.*

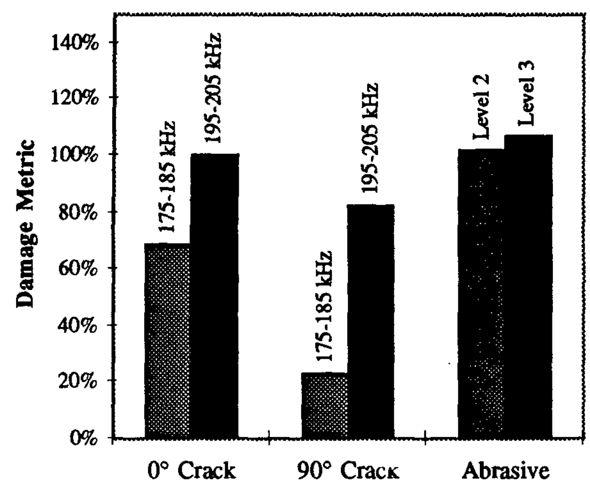

Figure 9. *The damage metric of all studied cases shows the frequency dependency of the health monitoring technique.*

Three-Bay Aluminum Truss [6]: Finally, the health monitoring technique was implemented on a three-bay aluminum truss. The purpose of this experimentation was the on-line implementation of a system using PZT actuator/sensors at multiple critical locations. Small PZT's (approximately 8 x 8 x 0.2 mm) were bonded to the eight nodes of the middle-bay. The impedance signature from each node was sequentially acquired and controlled by a personal computer. Damage was simulated by loosening one of the member's connection with the nodal Derlin-ball. Within the personal computer controller, the damage metric was computed and the health status of the structure was displayed in a green/red light fashion. Thus, through this investigation, the possibilty of implementing the technique on-line was confirmed.

ADVANTAGES OF THE NDE TECHNIQUE: The impedance-based health monitoring technique has been shown to be very efficient for the detection of incipient damage in complex structures. In summary, this new qualitative NDE technique has the following principal advantages:

- The technique is not based on any model, and thus can be easily applied to complex structures;
- The technique uses non-intrusive and small-size actuators to monitor inaccessible locations;
- The technique is unaffected by changes in boundary conditions, loading, or operational vibrations;
- The technique can be implemented for on-line health monitoring;
- The continuous monitoring provides a better assessment of the current status of the structure, which can eliminate scheduled base inspections;
- The added weight of the actuator/sensor is negligible.

CONCLUSION: A high-frequency impedance-based health monitoring technique is described. The method utilizes the changes in the electrical impedance of a surface-bonded PZT actuator-sensor, acquired through an impedance analyzer, as a qualitative indicator of damage. The five proof-of-concept applications showed the effectiveness of the new method in real-life complex structures. This technique, because of the high frequency, is very sensitive to minor damage, and the actuation-sensing area is limited to a small area. The localization of the sensing area provides a practical means of utilizing vibration/impedance measurements to monitor critical sections of structures.

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